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Abstract

The π^-/π^+ yield ratio in 1.05 GeV/nucleon ^{40}Ca + ^{40}Ca interactions was measured using a magnetic spectrometer system. The ratio was found to be unity over the entire range of measurements covering $\theta_{lab} = 10, 20, 25, 30, 65$ and 90 degrees and laboratory momenta $100 \leq p_{lab} \leq 350$ MeV/c. The ratios exhibit no visible effect of Coulomb forces from the nuclear charge distributions.

I. INTRODUCTION

Various enhancements have been reported in the π^+ yield and in the π^-/π^+ yield ratio in relativistic nucleus-nucleus collisions. Near the velocity of the beam, the π^-/π^+ yield ratio has been observed to be strongly enhanced in several reactions[1-3]. This enhancement has been explained in terms of the Coulomb interaction between the emitted pions and fragments of the projectile[4,5]. The present work relates to the π^-/π^+ yield ratio near the c.m. velocity, i.e. at midrapidity $y_{c.m.} = 0$.[6]

The π^+ yield has been reported to exhibit an enhancement near midrapidity in the reaction Ne + NaF at 800 MeV/nucleon [7,8] and in the reaction Ar + Ca at 1.05 GeV/nucleon.[9] However, in the reaction Ne + NaF at 400 MeV/nucleon[8] a smoothly-varying π^+ cross section with no enhancement was observed. In the p + p and p + nucleus reaction at 730 MeV a depression was observed[10] at midrapidity in the nucleon-nucleon c.m. frame.

The existence of a π^+ peak near midrapidity could be reproduced neither by intranuclear cascade calculations nor by predictions based on thermal models.[9] Suggestions were made that the π^+ enhancement might be due to collective hydrodynamic flow,[9] exotic delta or pionic states,[1,2] Coulomb focusing,[4,11,12] or other production mechanisms.[13-18] Incorporating final state π-nucleus electromagnetic effects,[4,11,12] qualitatively reproduced the π^+ peak at midrapidity when specific assumptions were made concerning the space-time development of the charge distributions of the nuclei during the collisions.

Results from the measurement of low energy π^- and π^+ cross sections at $\theta_{cm} = 90°$ [3,19] exhibit a smoothly-varying π^-/π^+ yield ratio in the Ar + KCl reaction at 1.05 GeV/nucleon and a peak in the Ne + NaF$\rightarrow \pi^-$ yield at 655 MeV/nucleon which does not agree with the Coulomb explanation.[4,11,12] In this paper we present more extensive experimental results on π^-/π^+ yield ratios which address the degree to which the Coulomb interactions between the pion and the charge distributions of the colliding nuclei affect the final pion momentum distributions.

II. EXPERIMENT

The yield ratios π^-/π^+ were measured in the isospin-symmetric ^{40}Ca + ^{40}Ca system at 1.05 GeV/nucleon using the Two Arm Spectrometer System (TASS) at the Bevalac. Details of TASS have been published elsewhere.[20] The two arms of TASS were deployed independently as shown in Fig. 1. In this experiment magnetic spectrometer 1 was implemented at angles $10° \leq \theta_{lab} \leq 30°$ and magnetic spectrometer 2 at $65° \leq \theta_{lab} \leq 90°$. In addition, a beam fragmentation scintillator array was used at $\theta_{lab} = 0°$. The forward spectrometer (magnetic spectrometer 1) was equipped with three scintillation hodoscopes (F0, F1 and F2) for position and time-of-flight measurement, a single scintillator element (F3) to start the timing electronics and an H_2O Cerenkov counter to distinguish electrons from pions. The rear spectrometer (magnetic spectrometer 2) incorporated two multi-wire proportional chambers (WC1 and WC2) with 2 mm wire-spacing, a scintillation hodoscope (R1) and two single scintillator elements (R2 and R3) for timing. Due to the higher position resolution of the wire chambers, the rear spectrometer arm had better resolution (2.0 % momentum resolution and 0.25° angular resolution) than the front arm (4.4 % in momentum and 0.33° in angle) and was able to distinguish electrons from pions based upon time-of-flight and the more accurate momentum measurement. The changes in the present experiment from that of Ref. 20 were the additions of a segmented F0 detector and a Cerenkov detector on the front arm, installation of the beam fragmentation array, and the use of helium bags in the front spectrometer and between the target and beam fragmentation array as shown in Fig. 1.

Natural Ca targets (96.94 % ^{40}Ca) of 0.5 g/cm^2 and 1.0 g/cm^2 were used. The position, shape and size of the beam on target were measured spill-by-spill in a wire chamber (BC in Fig. 1) with 2 mm wire-spacing, and stored on magnetic tape for subsequent analysis. The beam intensity in the experiment was limited to $\sim 8 \times 10^5$ per second to avoid excessive counting rates in the fragmentation array located downstream at $\theta_{lab} = 0°$. The absolute intensity of the beam was measured in a calibrated ionization chamber (IC in Fig.1) located upstream from the target, with an absolute accuracy of 20 percent. Also shown in Fig. 1 are two monitoring telescopes, each consisting of two inline scintillators, which were mounted above and below the beam viewing the ionization chamber. Ratios of counts in these monitoring telescopes and their count ratios relative to the ionization chamber counts were used to cross-check beam intensity and relative normalization between spectrometer settings.

Measurements of differential momentum spectra for both π^+ and π^- were made at $\theta_{lab} =$ 10, 20, 25, 30, 65 and 90 degrees over the momentum range 60 to 350 MeV/c. Up to three momentum settings, corresponding to central momenta of 80, 150 and 250 MeV/c, were used at each angle. No relative normalization was required between the various momentum settings of the spectrometers. For each angle and momentum setting, data were accumulated with and without a Ca target to facilitate subtraction of nontarget-related background. The polarities of the spectrometer magnets were alternated to enable data acquisition for both positively- and negatively-charged particles. Off-line selection using time-of-flight and pulse height in the scintillator and Cerenkov elements of the spectrometers made it possible to distinguish positively-charged pions from protons.

III. RESULTS

A complete mapping of the midrapidity region for both π^+ and π^- was made. The $p_\perp$ vs. y phase space covered by the experiment is displayed in Fig.2. The transverse momentum of the pion, $p_\perp$, is given in units of $m_\pi c$ where m_π is the pion mass and c the speed of light. The solid curves correspond to the laboratory angles and momentum ranges covered by the spectrometers. The dotted curves are the reflections of these curves about $y_{cm} = 0$. The hatched lines delineate the region in which measurements were reported in Ref. 9 where an enhancement in the yield of π^+ was observed at $0.3 < p_\perp < 0.5$ near midrapidity, i.e. $y_{cm} \sim 0$.

Detailed acceptance calculations using Monte Carlo techniques were made to correct for energy loss, multiple scattering in the target, air, helium and all spectrometer elements as well as pion decay-in-flight ($\pi \rightarrow \mu + \nu$). A calculation of the contribution of electron and positron contamination of the negative and positive pion spectra, respectively, was made using the geometrical acceptance of the TASS system. The ratio of electrons (positrons) to negative (positive) pions was found to fall exponentially as a function of momentum. This ratio falls below 10 percent at 100 MeV/c and below 2-3 percent at 150 MeV/c.

Due to the narrow momentum acceptances[20] of the spectrometers at the low central momentum settings of the magnets, edge effects in the acceptance precluded accurate determination of the differential cross sections for each charge state. However, since the acceptances are identical for positively- and negatively-charged particles at each pion momentum, for each setting of the magnets, the ratio π^-/π^+ can be determined as a function of momentum with only slight systematic uncertainty. The final π^-/π^+ ratios are displayed in Fig. 3 as a function of the pion laboratory momentum. The arrows indicate the momenta at which the enhancement was observed in the 1.05 GeV/nucleon Ar + Ca system for measured π^+.[9] The ratios are unity[21] within the statistical errors of the experiment, suggesting that there are no large Coulomb effects present.

Off-line multiplicity selection was made using the projectile fragmentation array. It was found that there are very few pions at midrapidity associated with particles of charge $Z > 1$ in the projectile fragmentation cone. This leads to the conclusion that on the average pions emitted at midrapidity are associated with central collision events where very little remains of the incident nuclei. This observation has also been reported in Refs. 22 and 23 and may provide a clue to the lack of Coulomb effects.

IV. DISCUSSION

The data measured in the present experiment cannot be used to address the question of the existence of a midrapidity peak. However, the observation of π^-/π^+ ratios equal to unity show definitively that the Coulomb focusing effect, which describes quantitatively the π^-/π^+ enhancement near beam rapidity, is small for pion production away from beam rapidity near 1 GeV/nucleon incident energy. The present results are consistent with previous measurements[3,19] of isospin-asymmetric systems.

The sensitivity of the π^-/π^+ ratios to effects of the Coulomb field of the protons can be estimated by calculating the difference in kinetic energies caused by a spherical charge distribution of protons on positive and negative pions assuming that the pions are outside the proton charge distribution. The resultant Coulomb distortions to the charged-pion energy spectra are primarily dependent upon the number of protons in the distribution and the radius of the distribution.[4,24] Results of this estimate can be used to ascertain the constraints that the measured π^-/π^+ ratios place on the proton charge distributions. Ratios of π^- and π^+ taken over a wide range of angles at lower energies for the La + La system[23] are consistent with a Coulomb distortion generated by half of the incident protons in a sphere of radius 1.15 $A^{1/3}$. The present ratios are consistent with a Coulomb distortion from a proton distribution with fewer than half the incident protons ($Z < 20$) and a larger radius for the proton distribution, in the range 1.15 $A^{1/3}$ to 1.6 $A^{1/3}$. This estimate assumes a static geometry. The dynamical evolution of the collision from initial impact through expansion is much more complicated. It is necessary to understand the dynamical evolution of the collision to be able to understand completely the π^-/π^+ ratios measured in experiments. Furthermore, comparisons of neutron and proton spectra[25] should be considered to complete the understanding of the dynamics of the collision.

Since the pions travei with higher velocity than the protons, whether they are produced by an expanding fireball or decaying Δ-resonances, one expects that they would be affected by the large Coulomb potential of the initial distribution of proton charges as described above. However, if the pions are emitted later and are trapped in the expanding nuclear matter, the Coulomb potential would be smaller and cause less distortion of the charged-pion spectra. Pion production in this energy range proceeds primarily through the Δ resonance. The Δ is heavier and on the average moves more slowly than the protons. It also has a finite lifetime, a few fm/c in the Δ rest frame, and subsequently decays into a pion and a nucleon. Intranuclear cascade calculations support this dynamical description and it appears that this latter scenario may occur. Another condition for this hypothesis to be plausible, is that the number of protons (and thus pions) from Δ-decay must be a small fraction of the total number of protons, i.e. the pion multiplicity is much less than the total number of protons. From the measured[26] negative pion multiplicity $< n_{\pi^-} > =$ 3.3 for central collisions of 1 GeV/nucleon Ar + KCl using the isobar model for the incident Ar + KCl system, this condition is met. The above conditions suggest that many pions are trapped in the form of Δ resonances inside the expanding nuclear matter and that the Coulomb effects on the observed π^- and π^+ spectra should therefore be small as observed in this experiment. A study of the charged-pion spectra in heavier systems should provide a more sensitive measure of the electromagnetic effects and of the dynamical evolution of the system.

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References

1. W. Benenson et al., Phys. Rev. Lett. 43, 683 (1979).
2. J.P. Sullivan, Ph.D. thesis, University of California, Lawrence Berkeley Laboratory Report LBL-12546 (1981); J.P. Sullivan et al., Phys. Rev. C25, 1499 (1982).
3. K.A. Frankel et al., Phys. Rev. C32, 975 (1985).
4. M. Gyulassy and S. K. Kaufmann, Nucl. Phys. A362, 503 (1981).
5. H.M.A. Radi et al., Phys Rev. C25, 1518 (1982).
6. Rapidity is defined as y= $(1/2)\ ln[(E+p_{||})/(E-p_{||})]$ with E the total energy and $p_{||}$ the component of momentum along the beam direction.
7. J. Chiba et al., Phys Rev. C20, 1332 (1979).
8. K. Nakai et al., Phys Rev. C20, 2210 (1979).
9. K.L. Wolf et al., Phys Rev. Lett. 42, 1448 (1979).
10. D.R.F. Cochran et al., Phys. Rev. D6, 3085 (1972).
11. K.G. Libbrecht and S.E. Koonin, Phys. Rev. Lett. 43, 1581 (1979).
12. J. Cugnon and S.E. Koonin, Nucl. Phys. A355, 477 (1981).
13. G.F. Bertsch, Nature 283, 280 (1980).
14. J.O. Rasmussen, Lawrence Berkeley Laboratory Report LBL-14174 (1982).
15. O. Scholten, H. Kruse and W.A. Friedman, Phys. Rev. C26, 1339 (1982).
16. H.M.A. Radi et al., Phys. Rev. C27, 606 (1983).

17. A.F. Barghouty and G. Fai, Phys. Rev. C35, 950 (1987).

18. A. Bonasera and G.F. Bertsch, Michigan State University Technical Report MSUCL-600, April 1987.

19. K.A. Frankel et al., Phys. Rev. C25, 1102 (1982).

20. R.N. Treuhaft, Ph.D. thesis, University of California, Lawrence Berkeley Laboratory Report LBL-14677 (1982); R.N. Treuhaft et al., Phys. Rev. C30, 616 (1984).

21. The ratios at low momenta for pions at $\theta_{lab} = 65\,°$ are an exception to this statement. As a cross-check of the data, the value of the ratio at the y_{cm} = -0.45, $p_\perp/m_\pi c = 0.6$ intersection in Fig. 2 was compared for the point on the $\theta_{lab} = 65\,°$ curve ($90 \le p \le 95$ MeV/c) and the point on the reflected $\theta_{lab} = 20\,°$ curve ($245 \le p \le 250$ MeV/c). As observed in Fig.3, this point has the ratio 0.6 in each of the two different measurements.

22. W.A. Zajc, Ph.D. thesis, University of California, Lawrence Berkeley Laboratory Report LBL-14864 (1982).

23. J. Miller, Ph.D thesis, University of California, Lawrence Berkeley Laboratory Report LBL-24275 (1988); J. Miller et al., Phys. Rev. Lett. 58, 2408 (1987) and 59, 519 (1987).

24. D. Ashery and J.P. Schiffer, Ann. Rev. Nucl. Part. Sci. 36, 207 (1986).

25. R. Madey et al., Phys. Rev. C34, 1342 (1986).

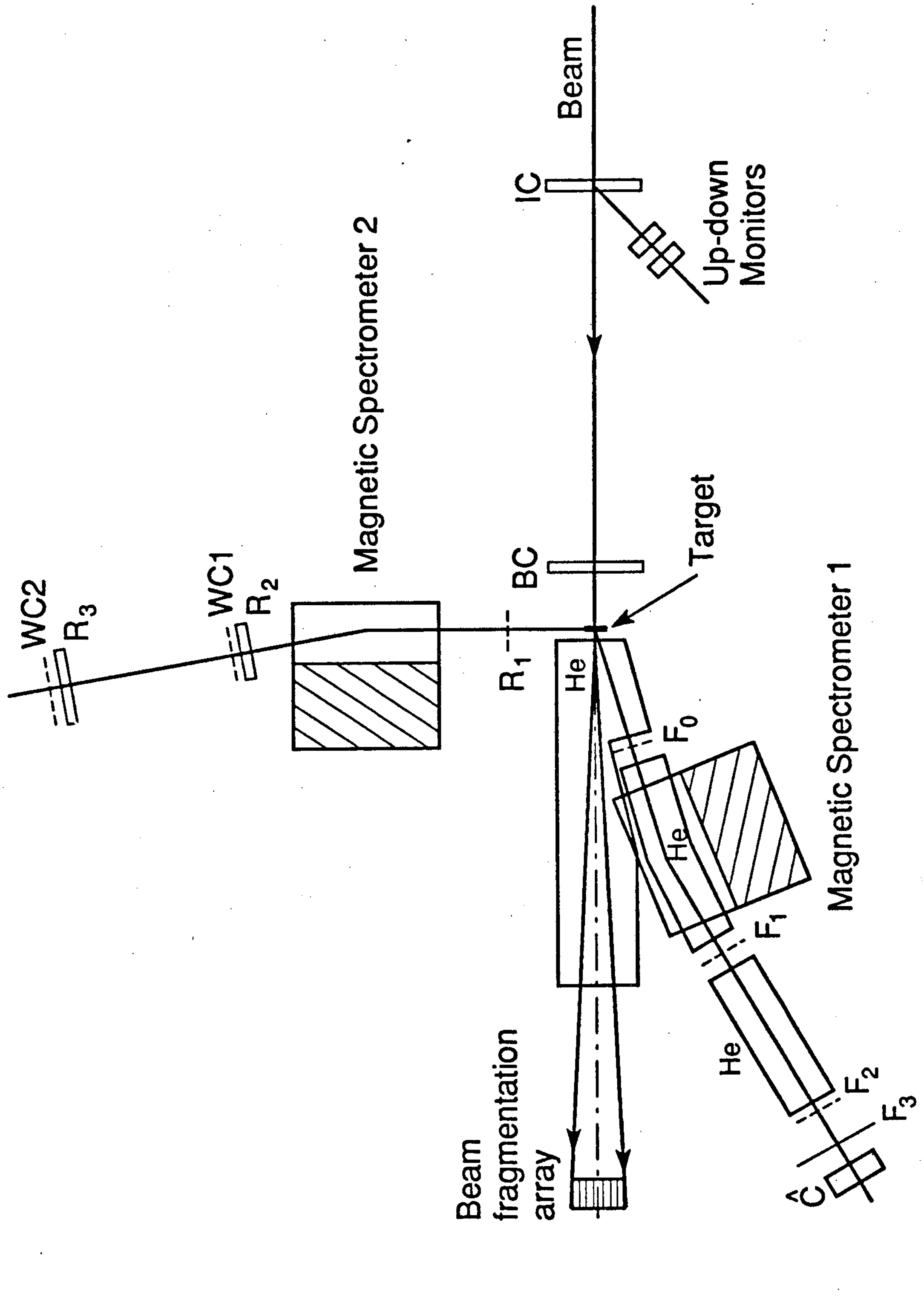
26. A. Sandoval et al., Phys. Rev. Lett. 45, 874 (1980).

Figure Captions

1. Schematic diagram of the Two Arm Spectrometer System used in the present experiment.

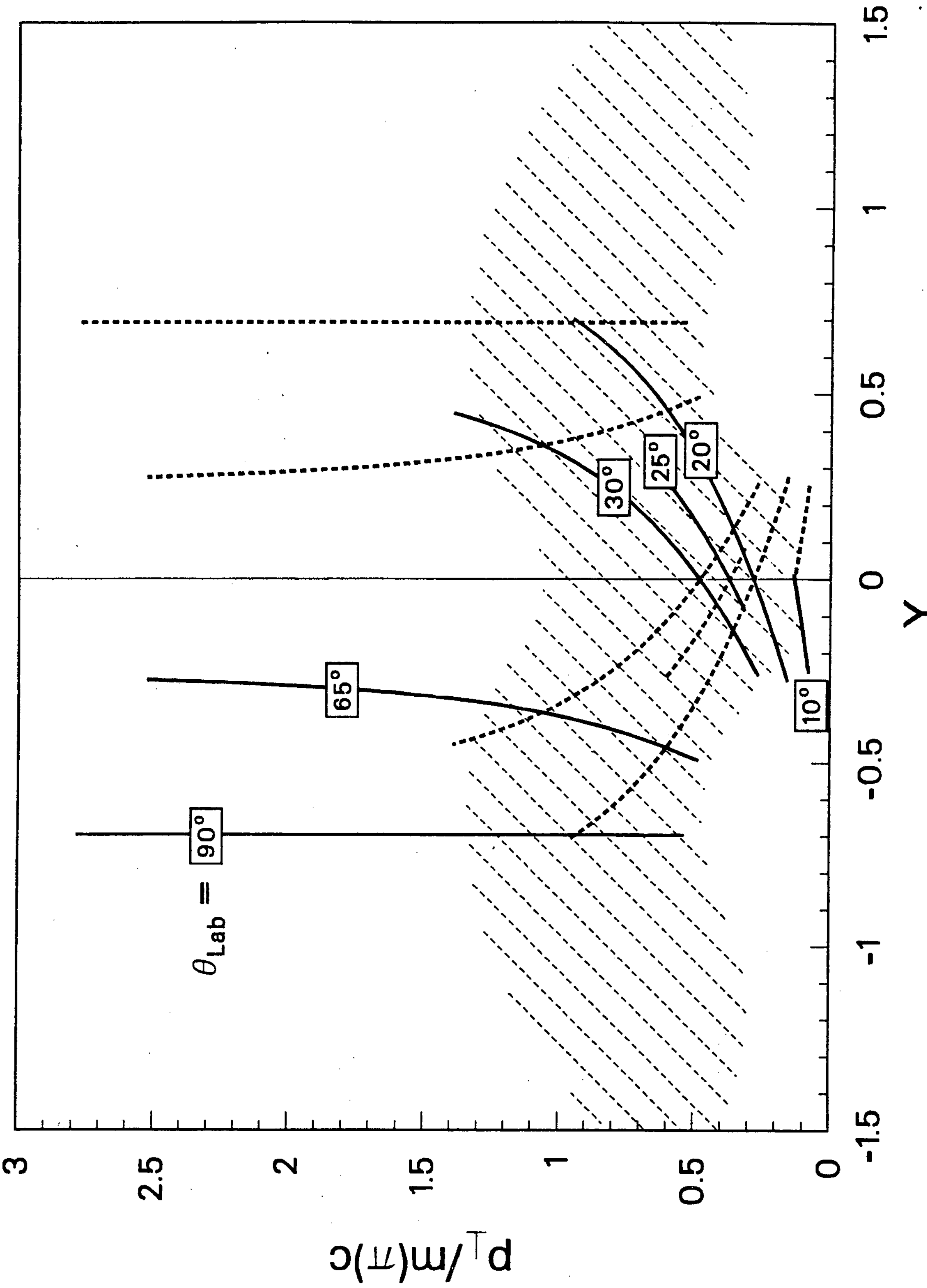
2. The $p_\perp$ vs. y phase space covered by the present experiment. The solid curves correspond to the ranges covered by the spectrometers for θ_{lab} = 10, 20, 25, 30, 65 and 90 degrees. The dotted curves are reflections of these angles about $y_{cm} = 0$. The hatched region is that in which measurements were reported in Ref. 9 with an enhancement reported in the yield of π^+ at $0.3 < p_\perp < 0.5$ near midrapidity, i.e. $y_{cm} \sim 0$.

3. The ratios π^-/π^+ as a function of momentum in 1.05 GeV/nucleon ^{40}Ca + ^{40}Ca interactions measured at θ_{lab} = 10, 20, 25, 30, 65 and 90 degrees. The arrows indicate the region of the broad enhancement in the π^+ yield at midrapidity reported in Ref. 9 for the 1.05 GeV/nucleon Ar + Ca system.



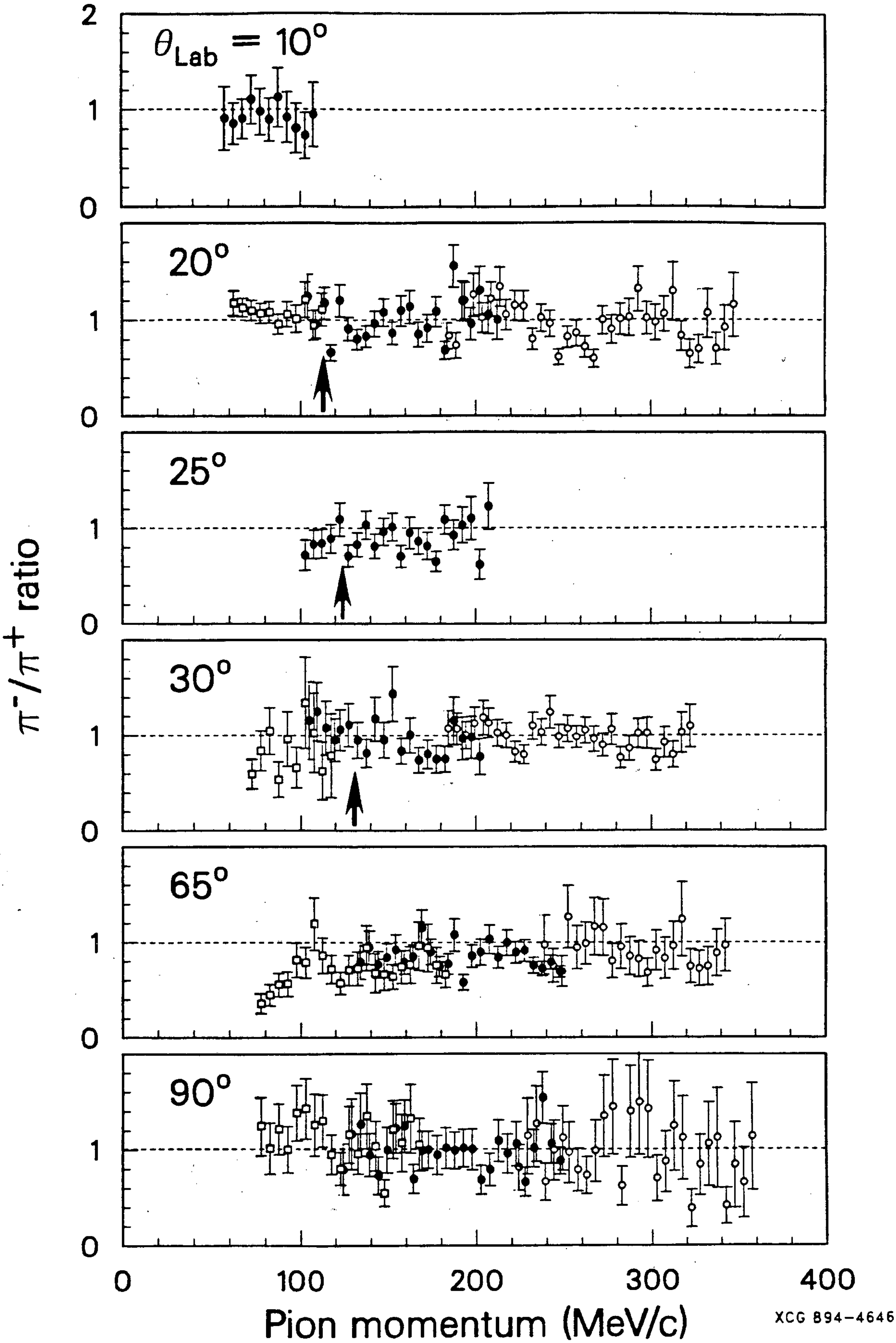
XBL 8411-4748A
TID/Mac/lg

Fig. 1



$p_\perp/m(\pi)c$
0
0.5
1
1.5
2
2.5
3
-1.5
-1
-0.5
0
0.5
1
1.5
$Y_{c.m.}$
θ_{Lab} =
90°
65°
30°
25°
20°
10°
XCG 894-4647 A

Fig. 2



$\theta_{Lab} = 10^o$
20°
25°
30°
65°
90°
π^-/π^+ ratio
Pion momentum (MeV/c)
XCG 894-4646

Fig. 3

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